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Simulation of G-Tolerance Curve Using
the Pulsatile Cardiovascular Model

This report presents a computer simulation study, performed to assess the ability of the cardiovascular model to reproduce the G-tolerance curve (G-level versus tolerance time). A composite strength-duration curve derived from experimental data obtained in human centrifugation studies was used for comparison. The effects of abolishing autonomic control and of blood volume loss on G-tolerance were also simulated. The results provide additional validation of the model. They point to the need for the presence of autonomic reflexes even at low levels of G. The low margin of safety with a loss of blood volume indicated by the simulation results underscores the necessity for protective measures during Shuttle reentry.

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SIMULATION OF G-TOLERANCE CURVE USING
THE PULSATILE CARDIOVASCULAR MODEL

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SIMULATION OF G-TOLERANCE CURVE USING
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ABSTRACT

This report presents a computer simulation study, performed to assess the ability of the cardiovascular model to reproduce the G-tolerance curve (G-level versus tolerance time). A composite strength-duration curve derived from experimental data obtained in human centrifugation studies was used for comparison. The effects of abolishing autonomic control and of blood volume loss on G-tolerance were also simulated. The results provide additional validation of the model. They point to the need for the presence of autonomic reflexes even at low levels of G. The low margin of safety with a loss of blood volume indicated by the simulation results underscores the necessity for protective measures during Shuttle reentry.

SIMULATION OF G-TOLERANCE CURVE USING THE PULSATILE CARDIOVASCULAR MODEL

INTRODUCTION

Our computer simulation study of cardiovascular responses during STS reentry reported previously (6) employed a mathematical model of the cardiovascular system that was originally developed to simulate responses to exercise (1). A somewhat simplified and slightly modified version of the model was utilized for simulating the responses to Lower Body Negative Pressure (LBNP) and tilt tests (2). These versions of the model were helpful in interpreting the cardiovascular data obtained from the manned Skylab flights and identifying possible underlying physiologic mechanisms (5). The ability of the model to reproduce cardiovascular responses to centrifugation was never tested, however, since the model, as designed originally, was not intended to simulate this condition. Therefore, the first task in our STS reentry study was the validation of the model to centrifugation responses.

Results of the simulation studies that we conducted to validate our pulsatile cardiovascular model for responses to $+G_z$ acceleration included steady-state and dynamic behavior and the G-tolerance curve indicating the strength-duration relationship. The purpose of the present report is to describe the details of the study on the simulation of G-tolerance curve.

METHODS

Experimental Data

The experimental data analyzed and published by Stoll (9) were used in simulation study presented here. These data were obtained at the U.S.N. Aviation Medical Acceleration Laboratory, Johnsville, PA. They were the results of 40 centrifugation runs with definite physiological end points performed on 15 subjects. All subjects were positioned in an effective upright seated position to receive $+G_z$ acceleration in these experiments. The stimulus acceleration was characterized by the following parameters (Fig. 1):

- (i) Rise time, defined as the time from the start of acceleration to onset of maximum G (T_r)
- (ii) Length of time spent at maximum G (T_m)
- (iii) Magnitude of maximum G
- (iv) Rate of acceleration to maximum G

It was essential to take into account the rate of acceleration because of its inverse relationship with the time to reach a physiological end point.

The data were examined for relationships among the total time (time from start of acceleration to physiological end point), the rate of acceleration, and the intensity of G. Stoll identified four types of physiological end points: (i) grayout, (ii) blackout, (iii) confusion with possible unconsciousness, and (iv) unconsciousness. Figure 2 summarizes the results of her analysis and clearly shows the increase in tolerance with a decrease of maximum G-level. Also, the dependence of the tolerance time on the rate of acceleration is evident from the fitted curve. At maximum G-levels between 3-G and 5-G, headward acceleration stresses can be tolerated for a longer period of time, provided the rate of acceleration is not larger than 0.2-0.3 G/sec.

Computer Simulation

The pulsatile cardiovascular model was used to simulate the G-tolerance curve shown in Figure 2. The total duration of each simulation run was 120 seconds, divided into three segments. For the first 40 seconds, the model was allowed to run with a tilt angle of zero, corresponding to the supine condition. The tilt angle was then changed to 90° corresponding to the sitting position. The parameters of the vascular compartments were set to simulate the subject sitting in the centrifugation chamber, and the run was continued for 30 seconds to allow the model to attain a steady-state. At this point, the parameters were readjusted (to simulate tilting of the centrifuge

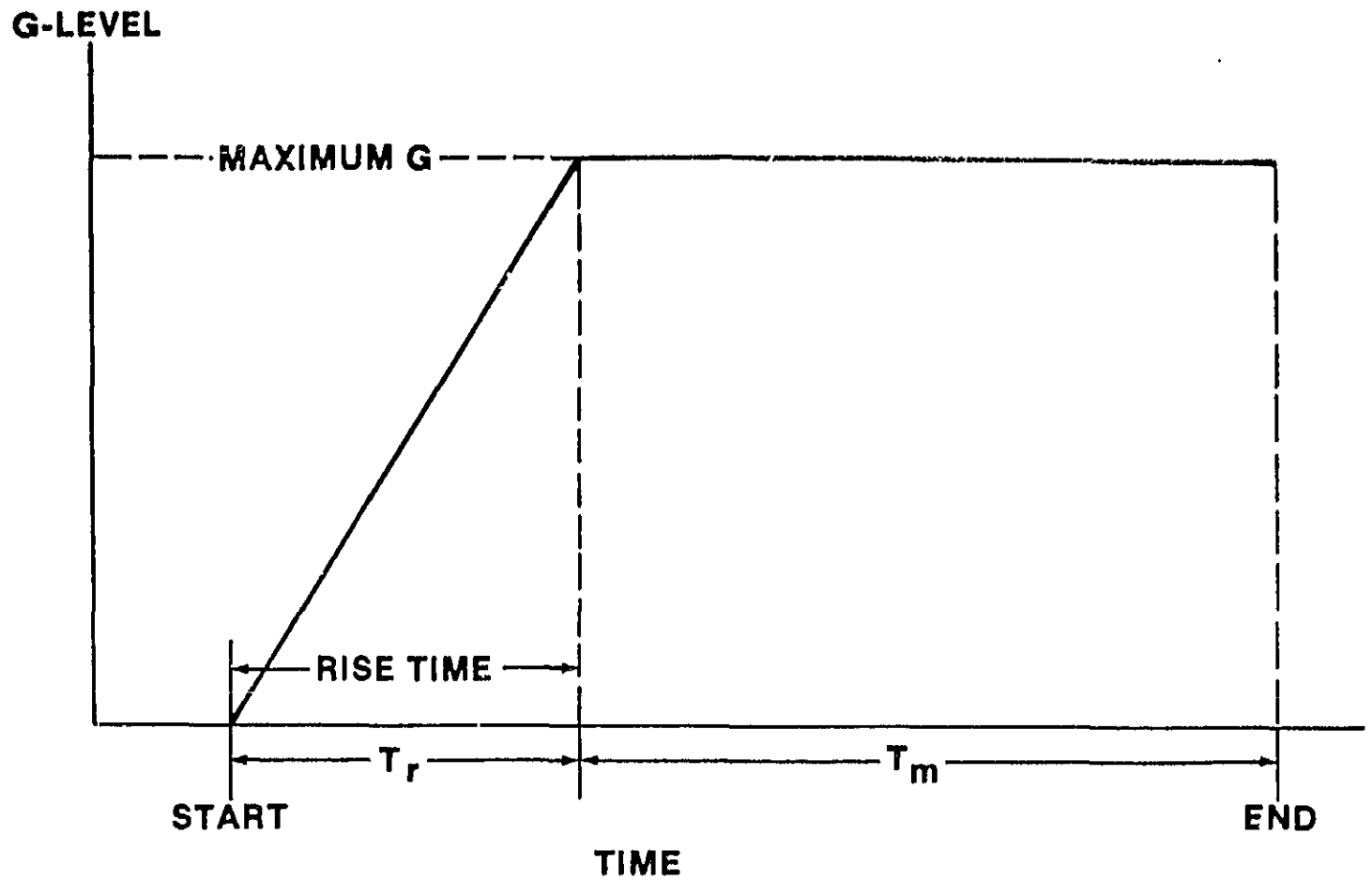


Figure 1: Acceleration profile used in centrifugation tests

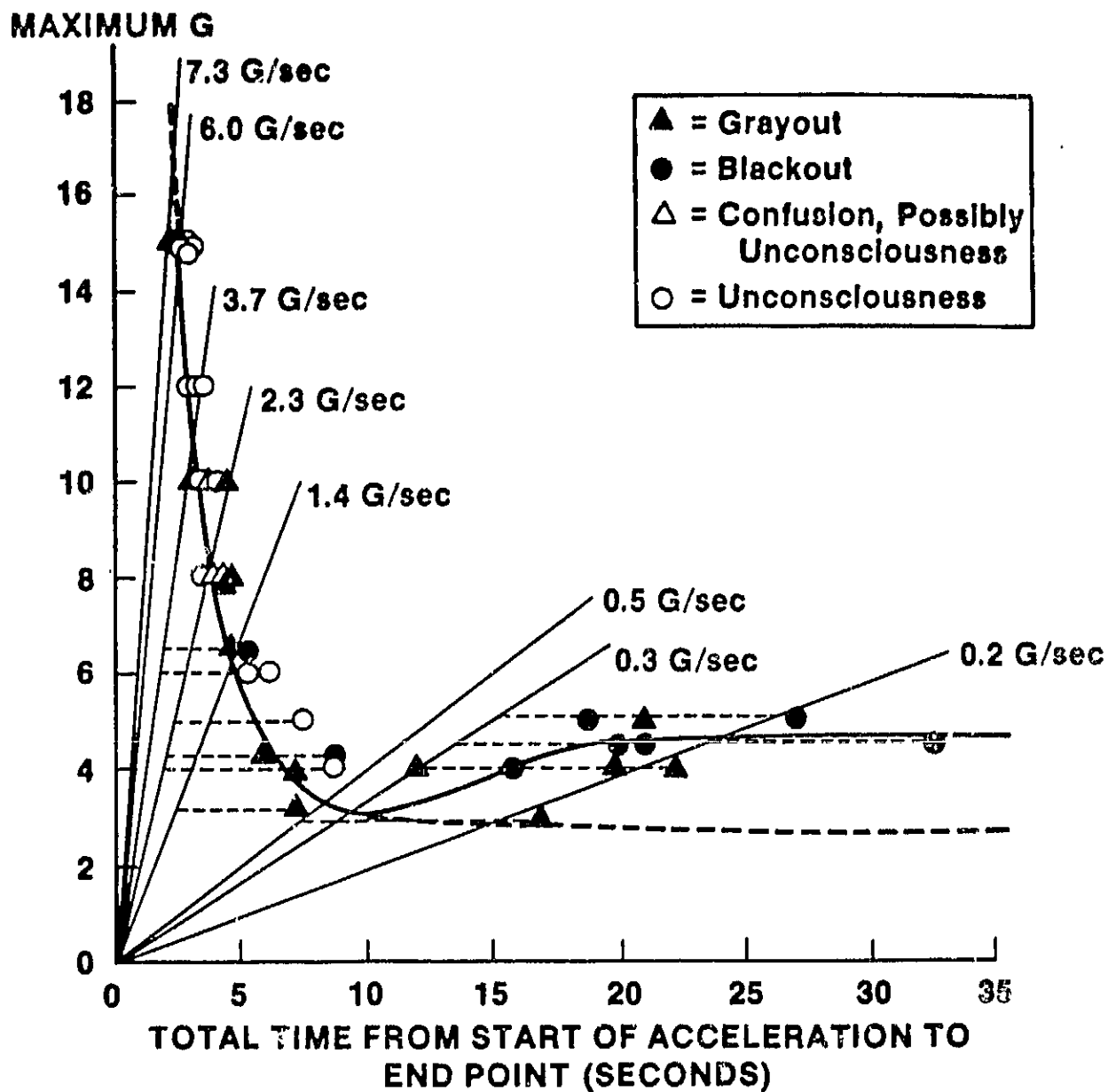


Figure 2: G-tolerance curve with various acceleration rates

Source: Stoll (9)

seat) and the acceleration stimulus was applied. This latter adjustment of parameters accounted for both the applied $+G_z$ acceleration and the normal 1-G force of the earth's gravitational field.

The acceleration stimuli were the same as those in Stoll's data, consisting of a ramp followed by a plateau. Several different maximum G values were used with acceleration rates of 0.2, 0.3, and 0.5 G/sec, in order to obtain a higher degree of resolution for this portion of the G-tolerance curve. There was no need to use more than one value of maximum G at higher acceleration rates of 1.4, 2.3, 3.7, 6.0, and 7.3 G/sec. It should be noted that the levels of G attained at these higher acceleration rates are well above those typically experienced by pilots and astronauts.

The results from the above set of simulation runs provided the data needed to demonstrate the ability of the model to reproduce the G-tolerance curve. After the initial validation was completed, another set of simulations were performed, with all parameters pertinent to autonomic control set at their minimum values. This eliminated effectively the influence of the autonomic control system. These simulation runs yielded data for comparison with Stoll's extrapolation of the G-tolerance curve (shown by dashed line in Fig. 2). The final set of simulation runs tested the effect of a reduction in the total circulating blood volume which is a well-documented effect of exposure to weightlessness (3,8).

Impairment Criteria

Blackout is defined to be the loss of both peripheral and central vision. This point is reached when systolic pressure at the head level falls below 40 mmHg (Fig. 3). Loss of peripheral vision with central graying occurs at systolic arterial pressures between 0 and 50 mmHg, with partial impairment occurring between 25 and 65 mmHg. The earliest point of onset of peripheral loss and central vision dimming occurs at 50 mmHg; this is also the average value when a partial peripheral loss is evident. For this reason, a systolic lower carotid arterial pressure threshold (APT) of 50 mmHG is defined here to be the point of functional impairment (PFI). At all lower values it is assumed that the average human is impaired to the point that he is unable to safely maneuver the craft he is flying.

RESULTS

Comparison of Simulated and Experimental Data

Figure 4 depicts a family of simulated curves, each derived by matching the duration from start of acceleration to attainment of a specified APT with the G level at that APT. Thus, points on each curve represent pairs of values for G-level and tolerance time at a given value of APT and is a boundary. All points above a curve represent systolic lower carotid arterial pressures smaller than the threshold value specified by the curve and vice versa. The curve derived by Stoll is also included for comparison.

The shape of the computer-generated curves show a precipitous drop in tolerance at acceleration rates higher than 1.4 G/sec. In fact, the tolerances for rates above this value are virtually identical. The curve fitted to the experimental data, on the other hand, shows a well-defined slope above 8-G. The discrepancy between simulated and experimental data may be due to inadequate sensitivity of the baroreceptor to rate of change of pressure in the model. No attempt was made to alter the rate sensitivity of the baroreceptor control. There was not great concern about data points above 8-G, because pilots, in general, only rarely approach G levels higher than 8-G and Shuttle astronauts experience no more than 2-G during reentry maneuvers.

The simulated curves for APT values of 60 and 50 mmHg (curves A and B in Fig. 4) exhibit a minimum point as does the experimental curve (curve D in Fig. 4). However, the location of the minimum point in curves A and B is different from that in curve D. The disagreement may be partially due to the way Stoll fitted the curve to the experimental data points. There appears to be enough scatter around the minimum (see Fig. 2) to justify its location anywhere between 3 and 3.5 G.

Both simulated and experimental data show a rebound effect. This portion of the curve demonstrates that, for a prolonged centrifugation run, a given G-level may be tolerated at a smaller acceleration rate whereas the same G-level may not be tolerable at a higher rate of acceleration. The final rebound values for the model-generated curve with an APT value of 50 mmHg are virtually identical to those of the experimental curve.

G-LEVEL

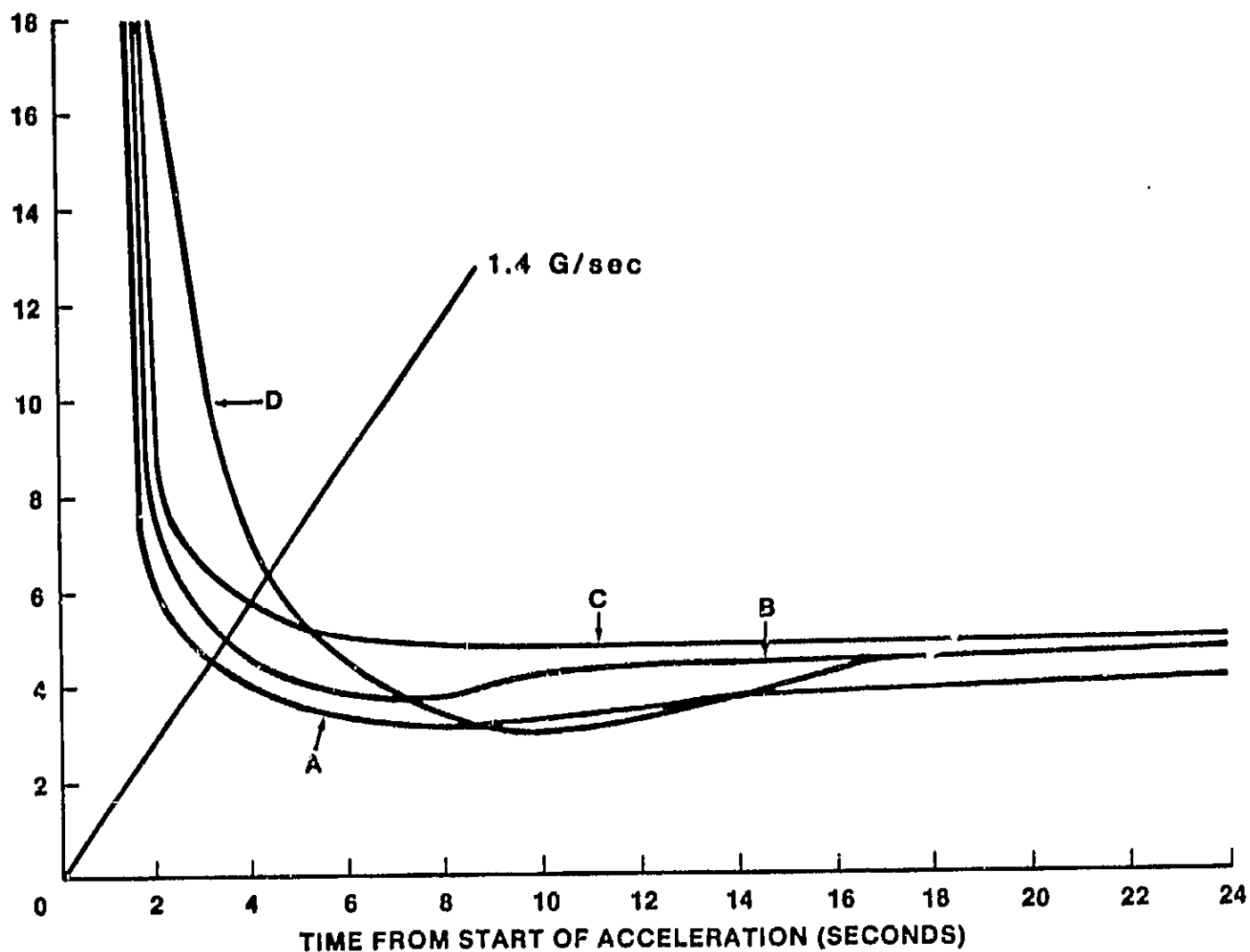


Figure 4: Simulated G-tolerance curves for various values of APT.
The experimental curve is also shown for comparison.

A: APT = 60 mmHg ; B: APT = 50 mmHg
C: APT = 45 mmHg ; D: Experimental Curve (9)

Considering both the minimum point and the rebound effect discussed in the preceding paragraphs, the simulated curve that best reproduces the shape of the experimental curve is curve B, corresponding to an APT value of 50 mmHg. The deviation between the two is further diminished by shifting the simulated curve to the right as indicated in Figure 5. This figure shows the effect of including compensation for a two-second delay. The correction accounts for the time between the point at which the blood pressure falls to a level capable of producing a PFI and the point at which the functional impairment actually occurs (4). The delay is due to the inherent oxygen supply available to the central nervous system and is of the order of two seconds.

Effect of Removal of Autonomic Control

Computer simulations were performed by setting the parameters relating to autonomic responses at their minimum values, thus effectively removing the autonomic reflexes from the model. Figure 6 shows a representative curve from these simulations with a PFI criterion of APT = 50 mmHg. The model-generated curve deviates significantly from Stoll's extrapolation (shown by dashed line in Fig. 2) to predict the shape of a curve devoid of cardiovascular reflexes. The model shows that the curve without autonomies is not merely a straight line extension from the minimum point of the curve obtained with intact autonomies. Rather, there is a divergence beginning at 6-G with a greater slope for the curve without autonomies. In addition, this curve seems to continue to slope downward, perhaps becoming asymptotic between 1 and 1.5 G.

On the basis of extrapolation, Stoll suggested that accelerations up to 3-G should be tolerable for an indefinite period of time with no autonomic reflexes active. The results of the present simulation indicate that Stoll's extrapolation, in contrast to her hypothesis, does depict the presence of reflexes, although they are partially impaired and operate only to maintain a reduced tolerance level. The continued assault of a given rate of acceleration will constantly increase the G force to which the subject is exposed. With no autonomic reflexes this means that blood in the head is under a constantly increasing force in the $+G_z$ direction, with no means to

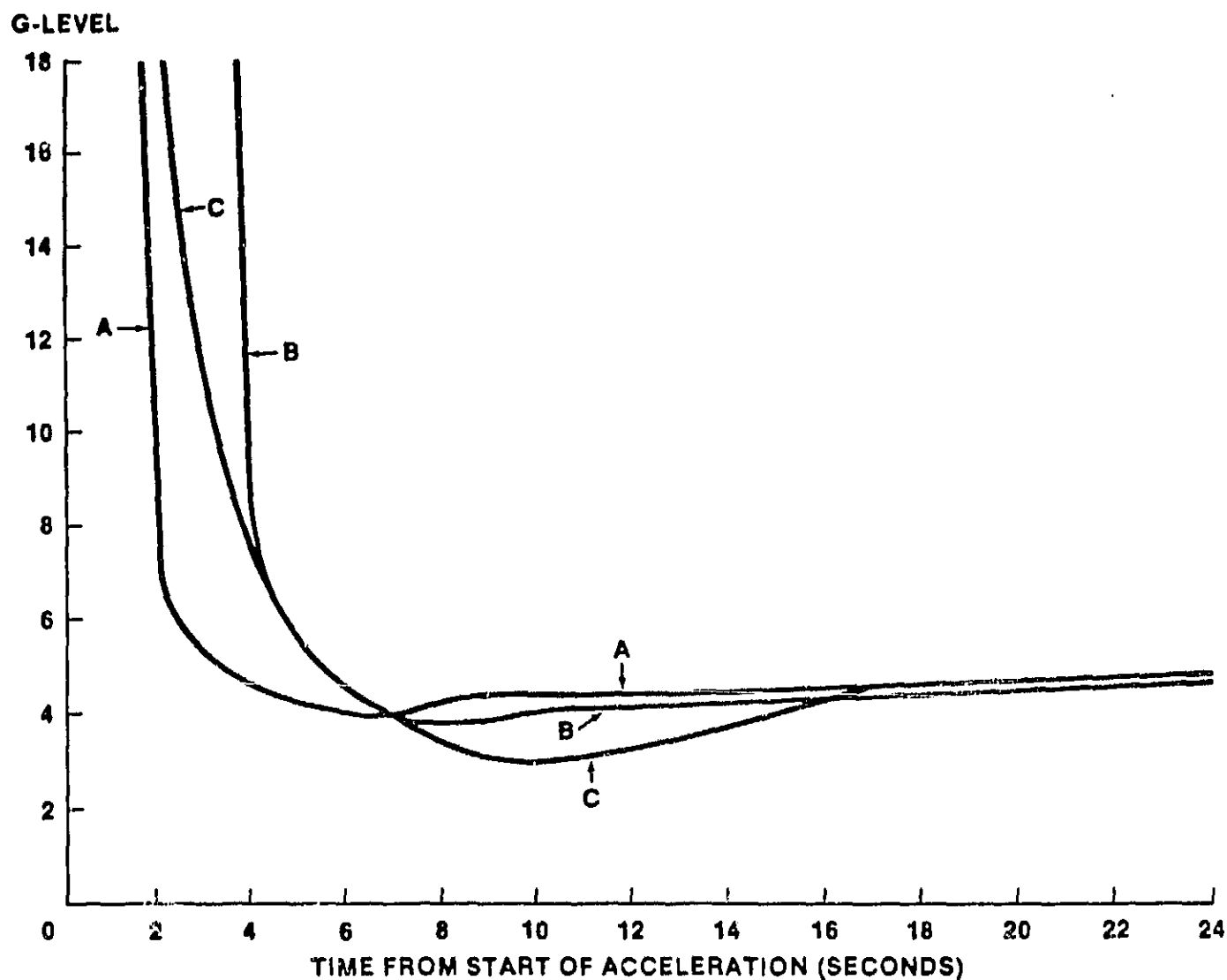


Figure 5: Effect of including compensation for two-second delay. APT = 50 mmHg

- A: Without Compensation
- B: With Compensation
- C: Experimental Curve (9)

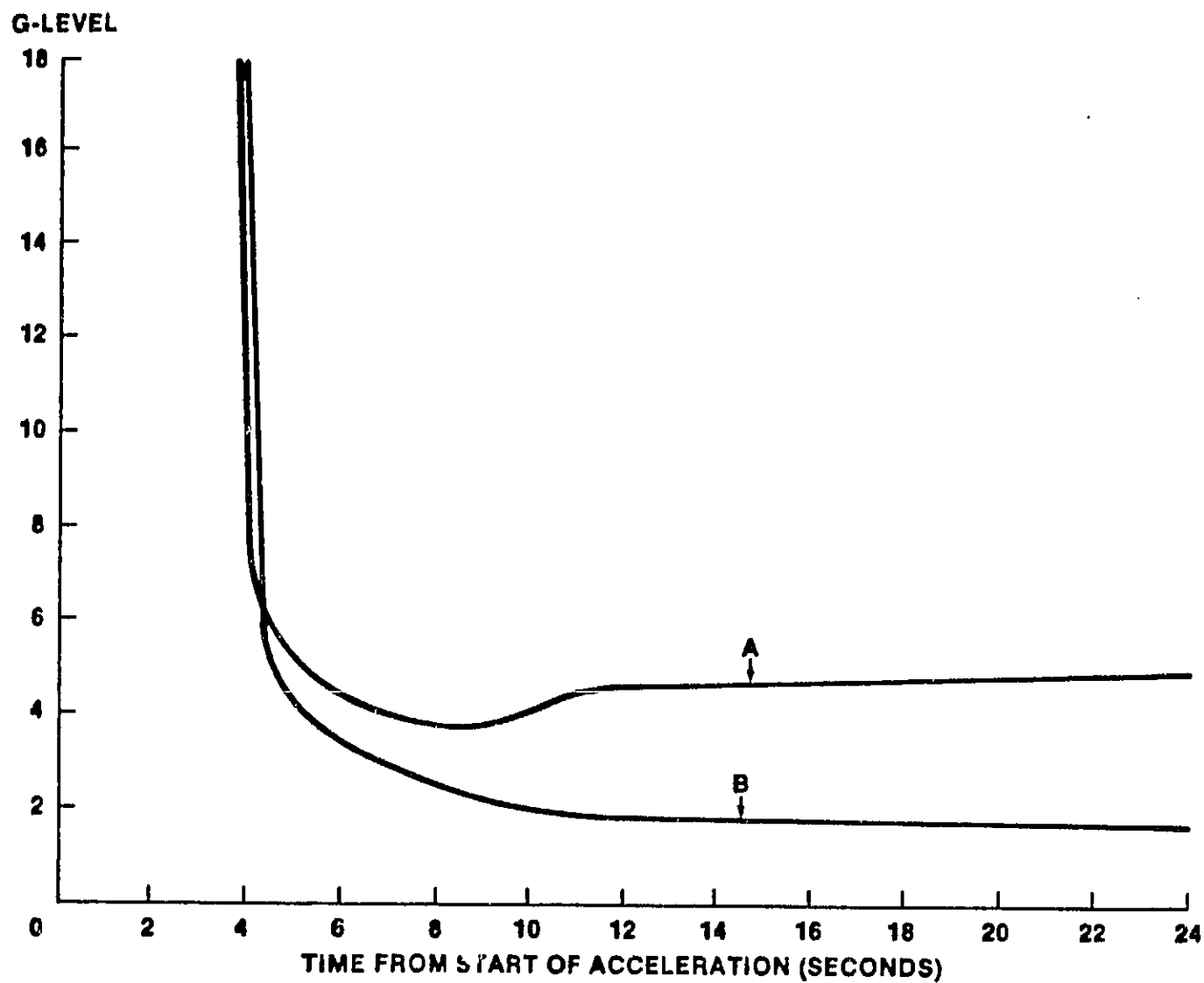


Figure 6: Comparison of model-generated curves with intact autonomic reflexes (A) and with autonomic excluded (B).

Curves include two-second compensation. APT = 50 mmHg

overcome that force. Under these circumstances, it seems unreasonable that tolerance would remain constant. Thus, Stoll's hypothesis appears untenable in the light of our simulation results.

Effect of Blood Volume Loss

Simulations were performed by setting the total circulating blood volume (BV) to levels below its nominal value (5000 ml) in the model. The purpose was to simulate the G-tolerance of astronauts following an exposure to weightlessness with a consequent reduction in blood volume.

Figure 7 shows results obtained with a blood volume loss of 10 percent. Simulated curve obtained with no blood volume loss and an APT value of 50 mmHg and the experimental curve of Stoll (curves B and D of Fig. 4) are also included for comparison. The most obvious result of a blood volume loss on tolerance to $+G_z$ acceleration is the absence of a rebound effect. The dependency of G-tolerance on the rate of acceleration is no longer present. Also, the simulated curve with a blood volume loss is almost identical to that in Figure 6 with autonomies excluded. Thus, it appears that intact autonomic reflexes and a blood volume close to normal are both essential in order for a rebound effect to be evident, indicating the influence of the rate of acceleration upon G-tolerance.

Space Shuttle crewmembers generally experience approximately a ten percent reduction in BV as a result of exposure to a weightless environment. The simulation results with BV loss in Figure 7 show that, after five seconds, the PFI is reached approximately between 2 and 2.5 G. Since the previous Shuttle crewmembers have been exposed to 1.75 - 2 G upon reentry, it is evident that they may come close to experiencing functional impairment. As long as the reentry stress is kept below 2-G and BV loss is less than 10 percent, the likelihood of impairment of the average crewmember is low. However, it is known that humans can be classified as fainters or non-fainters. The present configuration of our model uses an average cardiovascular system. A future study may attempt to modify the model to simulate fainters and non-fainters under the various conditions used in the present investigation.

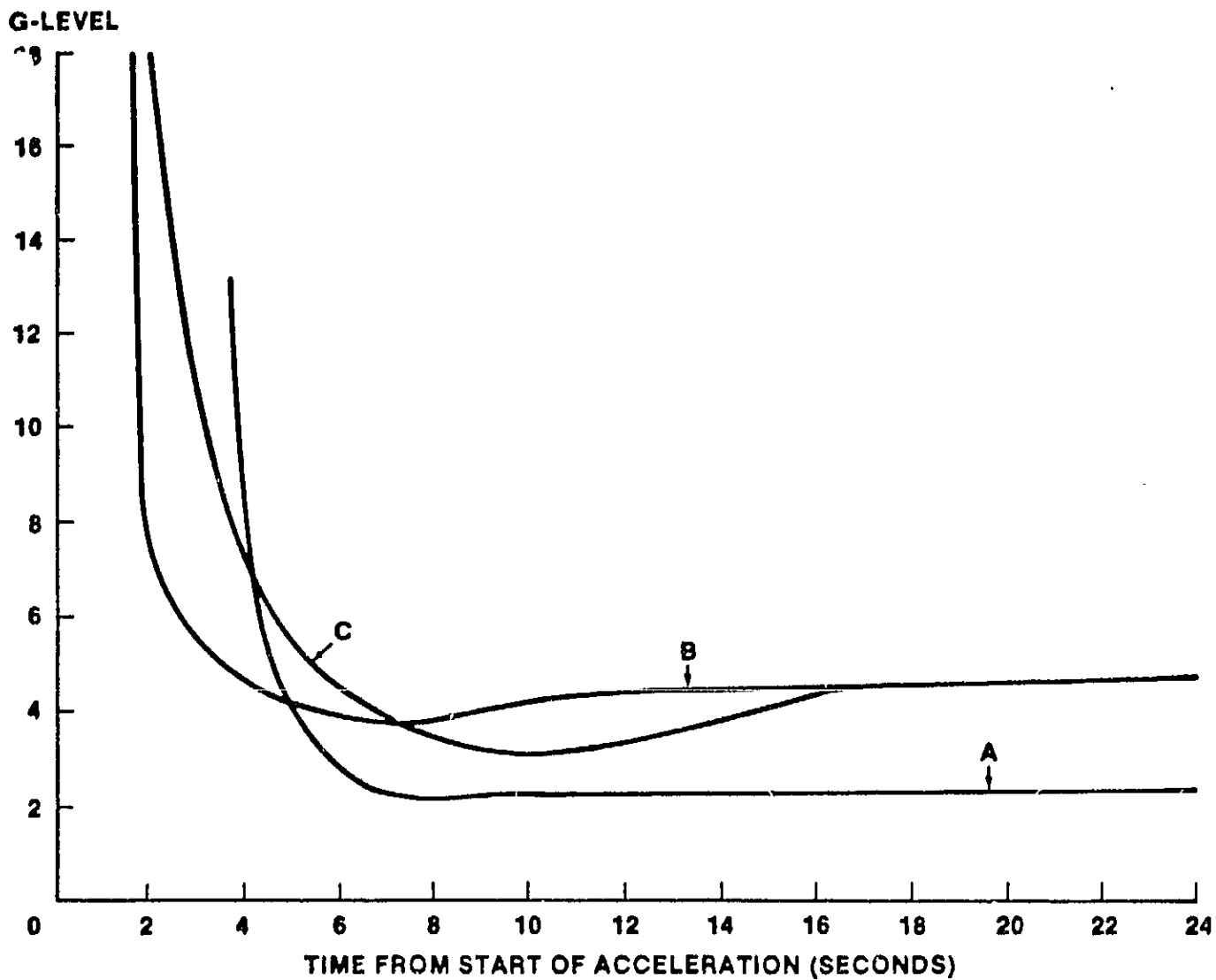


Figure 7: Effect of blood volume loss on G-tolerance. APT = 50 mmHg

- A: With 10 Percent Loss of Blood Volume
- B: With No Loss of Blood Volume
- C: Experimental Curve (9)

The results of simulations with reduced BV also suggest that the margin of safety during Shuttle reentry is quite small. Assuming that PFI occurs between 2 and 2.5 G, and that normal reentry acceleration is between 1.75 and 2 G, it is prudent to take protective measures such as fluid loading so as to enhance the safety margin.

CONCLUSIONS

This study has provided additional validation of the pulsatile model to centrifugation responses utilizing human physiological data on the strength-duration relationship for positive G-tolerance. The model is capable of simulating the main features of the G-tolerance curve derived from experimental data. In terms of reproducing the presence of a minimum point and a rebound effect, the model yields best results if

- (i) A threshold level of 50 mmHg for systolic lower carotid arterial pressure is used for defining the point of functional impairment, and
- (ii) The inherent delay between attainment of threshold pressure level and the production of symptoms is taken into account.

Results of simulations with removal of autonomics point to the need for the presence of autonomic reflexes even at low levels of G. This is at variance with the hypothesis suggested by Stoll and needs additional experimental data for clarification and resolution.

Both, exclusion of autonomic control and a loss of blood volume tend to remove the influence of rate of acceleration on G-tolerance (the rebound effect). The decrease of tolerance due to diminished blood volume is particularly significant during Shuttle reentry. The small margin of safety indicated by the simulation results warrants the need for protective measures during reentry.

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